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Towards Predicting Pesticide Deposition from Plant Phenology; a Study in Spring Barley

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Abstract: The relationship between crop architecture and spray interception was investigated in spring barley at two developmental stages. Height and outer surface area were determined for stems, leaves and ears, when present. To trace the droplet interception by the crop a fluorescent dye was used. To avoid difficulties in measuring spray deposition on plant surfaces, the non-intercepted pesticide at different heights in the air between the plants was determined from the deposit on glass strips placed horizontally at different crop strata. A regression model was used to relate the glass strip measurements to the plant surface measurements.

Analysis of the crop architecture indicated that the position and size of the leaves, the stem thickness and stem surface could all be described as a function of the height of the flag leaf. Analysis of deposition measurements showed that stems, leaves and ears all contributed significantly to spray interception, which correlated in a log-linear way with plant surface. The plant surfaces of stems, leaves and ears showed no significant differences in the fractions of droplets that were captured per unit of surface area, which fraction was indicated as the '*k* value'. This showed that the droplet interception in spring barley could, in principle, be modelled using a single coefficient. As a one-parameter model would restrict interpretability and comparability of the present results with other studies, the approach with separate *k* values was nevertheless preferred when analysing the deposition pattern in the crop and on the soil. The prospects of using crop height as the main model parameter for crop architecture in future predictions of pesticide deposition in cereals are discussed. © 1998 SCI

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Key words: crop strata; leaf area; crop stage; crop architecture; pesticide deposition; plant phenology

1 INTRODUCTION

Pesticide (side-)effects on plant-dwelling organisms are caused by uptake *via* different routes following topical exposure to sprayed droplets, exposure to vapour of volatile compounds, oral uptake *via* contaminated food, and dermal uptake following contact with pesticide residues on plant surfaces or soil. In this paper we focus on the cause of residual exposure, by quantifying the amount of pesticide which reaches different crop strata after spraying. Not all plant parts receive equal amounts of a spray. The interception of droplets during their journey through the crop causes the lower parts of the plants to be the least exposed.[1,2] The soil, finally, captures the droplets that do not end on plant surfaces. The interception of pesticide spray by the plant can be modelled from the droplet interception capacity of the plant per unit of plant surface and the total surface above any particular height of interest. Different publications show that the interception is affected by windspeed and electrical charging of droplets,[3] growth stage,[1,4] angle of the leaf surface relative to the horizontal or vertical plane and droplet size spectrum of the spray.[3,5] A detailed theoretical model which calculates

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the droplet interception from horizontal and vertical plant surfaces and takes into account wind speed and the droplet size spectrum has been published by Bache.[6] Such detailed models help to understand the process of pesticide deposition in a crop canopy, especially when it comes to droplet size distributions. They are, however, not easy to apply to field data because they require measurements of many parameters. It remains an open question, therefore, how elaborate a model has to be, especially if we take into account that farmers can only supply rapidly measurable crop parameters. Another argument in favour of simple models is that field results appear to be relatively insensitive to spray conditions. In particular the spray volume rate and the initial droplet size have little effect on the final deposit at different crop strata, as has repeatedly been demonstrated.[1,7] Compared to the effects of these application techniques, the deposition is influenced much more by crop stage and related plant surface area.[1,4] This shows that the plant surface must be considered as a major variable in explaining deposition measurements. Yet field observations hardly ever aim at describing or predicting total plant surface from crop architecture and seldom contain information about stratified measurements of deposition and crop surface. This situation was also highlighted for attention by Kjølholt[8] in a review of pesticide distribution in crops and the predictions made by models. The aim of the present study was to investigate the predictability of crop architecture and to analyse the importance of interception by different types of surfaces in a spring barley crop.

2 MATERIALS AND METHODS

2.1 Field trials

The present data set integrates results from three separate experiments. In the first experiment a 'stems only' barley crop was simulated by placing on a square metre 586 metal rods of 60 cm height and 0·312 cm diameter, which corresponds to the average stem diameter of spring barley. The rods were sprayed with tap water to which 0·5 g litre^{-1} fluorescent dye had been added. Deposition was measured on horizontally positioned glass strips, 3 × 27·5 cm, which were either placed on the soil or on rods of 10, 20, 30, 40, 50 and 60 cm height. Three glass strips were used per height. Positions of the glass strips in the plot were random.

The second experiment involved three spring barley plots of 12 × 2 m which were sprayed in sequence with tap water containing 0·5 g litre^{-1} fluorescent dye, with tap water with tracer and 1·4 g AI litre^{-1} dimethoate (Dimethoate 280 g litre^{-1} EC, Esbjerg Kemi, Denmark), or with tap water with tracer and 0·0625 g AI litre^{-1} cypermethrin (Cyperb 100 g litre^{-1} EC, DLG, Denmark). Within each plot, pesticide deposition was measured in triplicate on glass strips at 0, 10, 20, 30 and 40 cm height, and the leaf and stem surfaces of the barley plants were measured at the locations where the glass strips were placed. Date of spraying: 20 June 1996. Plant stage: 47 (flag sheath just opened).[9]

Experiment 3 was performed in the same field as experiment two. By cutting stems away, four plots of one m^2 were created with (nominal) stem densities ranging from 100%, *via* 75 and 50, to 25%. Spring barley plants were sprayed with tap water containing 0·5 g litre^{-1} fluorescent dye. In each plot, plant area was sampled and deposition was measured in triplicate using glass strips at 0, 10, 20, 30, 40 and 50 cm. Date of spraying: 27 June 1996. Plant stage: 56 (75% of ear emerged from flag sheath).[9] An overview of experimental layout and summary of crop parameters for the above experiments is given in Table 1.

In all the above experiments, the deposition of fluorescent dye was measured on 3 × 27·5 cm glass strips which were positioned horizontally in the crop canopy. Long strips were used to obtain accurate mean values of deposition in the crop canopy where leaves may locally form clusters and thereby cause considerable variation if deposition were measured using small areas. The glass strips were considered to be broad enough to avoid measurements being affected by possible rebounding of droplets from the glass plates. Observations showed that droplets both with and without pesticide always spread immediately upon contact with the rinsed glass surface. The fluorescent tracer used was 'Fluorescein Natriumsalz' ('Acid Yellow 73; Aldrich Chemie, Steinheim, Germany; spectrophotometric concentration measurements, excitation 495 nm, emission 515 nm). In all experiments, spraying was conducted using a portable azo spraying boom (200 cm length with 9 Hardi 110 flat-fan nozzles type 4110-16 at 25-cm intervals, spraying pressure: 2 bar, height above the crop: 30 cm). As only relative measurements of deposition at the different crop strata were required for the present analysis, calibration of deposition by means of walking speed was not attempted. To avoid photo-degradation of the fluorescent tracer, the experiments were performed at twilight or dawn and all glass strips were put into a light-tight box within 3 min after spraying. Fields were sprayed with solutions which in some cases did contain the formulated insecticide, and in other cases contained only water. Compared to the influence of leaf area, the effect of this was expected to be small. During field applications the wind speed was always below 1 m s^{-1}.

The following procedures were used to assess crop surfaces. The stem density was determined from 0·33-m^2 samples at the locations of the glass strips. These samples were weighed, and sub-samples of 15 straws (experiment 2) or 20 straws (experiment 3) were taken and were also weighed. These small samples were used to measure area and height of the stems, and the surface and height of every leaf and, when present, the ears. Surfaces were measured using a LI-3100 Area Meter

TABLE 1
Experimental Layout and Summary Parameters for the Crops Used

Experiment	*Spray No.*[a]	*Sub-plot*[b]	*Frequency*[c]	*Tillers* (*no.*)	*Stem area*[d] ($m^2\ m^{-2}$)	*Leaf area*[d] ($m^2\ m^{-2}$)	*Ear area*[d] ($m^2\ m^{-2}$)	*Total area*[d] ($m^2\ m^{-2}$)
Exp. 1	1	1	—	568	3·45			3·45
Exp. 2	2	2·1	49·3	741	3·20	9·16		12·36
	2	2·2	34·6	519	2·17	5·76		7·93
	2	2·3	41·6	624	2·70	7·34		10·04
	3	3·1	36·3	544	2·58	6·06		8·64
	3	3·2	40·8	612	2·54	6·46		9·00
	3	3·3	42·9	643	3·08	6·38		9·46
	4	4·1	42·2	633	2·64	6·58		9·22
	4	4·2	40·1	610	2·48	6·30		9·14
	4	4·3	37·0	554	2·48	6·22		8·70
Exp. 3	5	5·1	14·6	756	4·18	6·40	1·79	12·37
	5	5·2	24·4	624	3·11	4·36	1·38	8·85
	5	5·3	31·2	489	2·61	4·00	1·06	7·68
	5	5·4	37·7	291	1·63	2·58	0·65	4·87

[a] Spray number relates to different spraying events.
[b] One-square-metre areas in which measurements were made.
[c] Multiplication factor to relate samples of 20 or 15 tillers to square metre values.
[d] All values represent total outer surface (see Section 2.1).

(LI-Cor., Inc. Lincoln, Nebrasca, USA) which measures surfaces as flat projections of the plant parts. These measurements were transformed into total outer surface values. This was done to obtain the same units for all plant parts, which is necessary if one wishes to make the value of the regression coefficient for the intercepted fraction of pesticide per unit of plant surface, k, comparable between plant parts and experiments. Total outer surface was calculated by multiplication of the leaf measurements by 2, and of stem and ear measurements by π. Using the relative weights of the 15 and 20 straw subsamples, and a factor 3 to account for the soil area of the field samples, leaf area measurements were transformed to square metre values.

2.2 Crop architecture

A description of crop architecture was included to increase the understanding of how this may be used to improve the predictive capacity of deposition models in future experiments. As the present sub-sample covered only two crop stages, the relationships were considered insufficient to attempt to build a deposition model based on predicted crop architecture. The following aspects of crop architecture were analysed: leaf position and leaf surface in relation to plant height, and stem surface in relation to stem length and growth stage. The position above the ground and the surface of the leaves were related to the height of the flag leaf. As an indication of leaf height, we used the positions where the leaf separated from the stem, not the height of the nodes. The relationship between stem length and stem area was analysed using the following expression for isomorphic growth:

$$A(t) = A(0)^* \frac{l(t)^2}{l(0)^2} \tag{1}$$

where $A(0)$ and $A(t)$, and $l(0)$ and $l(t)$ represent the area and length of the stems at time zero and t, respectively. By rearranging we obtained a linear relationship between the square root of the measured stem area and its length:

$$\sqrt{A(t)} = l(t)\sqrt{\frac{A(0)}{L(0)^2}} = l(t)^*C \tag{2}$$

in which C is a constant.

2.3 Regression model

The interception of droplets by the crop was modelled in close analogy to the work of Graf *et al.*[10] on the interception of light by rice and weed plants. Instead of using different plant types with the same interception coefficient, however, we used a single plant type, namely spring barley, in which we allowed for independent interception coefficients of the area of stems, leaves and ears. Interactions between the effects of different area types, such as may result from a shading effect of leaf surface on deposition on stems, were assumed negligible because the stem length between two leaves was in general approximately 10 cm, the leaves can only shade the stem from one direction, and the droplets are

sprayed from many angles from the nozzles. Accordingly, the interception of droplets in the crop by stems, leaves and ears could be related to the respective surfaces as follows:

$$\frac{dC}{dx} = \left(-k_1 \frac{dS_1}{dx} - k_2 \frac{dS_2}{dx} - k_3 \frac{dS_3}{dx} \right) \cdot C \qquad (3)$$

Here, C (mol m^{-3}) is the total amount of pesticide in the air at a given height, dC the decrease in this over the height interval dx, k_1, k_2 and k_3 (m^{-2}) are the respective interception coefficients for stem surface, leaf surface and ear surface, and dS_1, dS_2 and dS_3 represent the increase in outer surfaces (m^2) for stems, leaves and ears, respectively. Integration of this equation yields:

$$C(x) = C(0) \cdot \exp[-k_1 S_1(x) - k_2 S_2(x) - k_3 S_3(x)] \quad (4)$$

where $C(x)$ is the amount of pesticide in the air after the spray has passed the total plant surface above height x, $C(0)$ is the initial rate of application of the sprayed pesticide, $S_1(x)$, $S_2(x)$ and $S_3(x)$ represent the cumulative plant surfaces above height x, for stems, leaves and ears, respectively. The amount of pesticide captured by the cumulative leaf surface above height x can now be expressed as:

$$C(0) - C(x) = C(0)\{1 - \exp[-k_1 S_1(x) - k_2 S_2(x) - k_3 S_3(x)]\} \quad (5)$$

After logarithmic transformation to account for the increase in variance with increasing deposition values, eqn (4) was used to fit the relationship between pesticide deposition on the glass strips and the surface measurements of stems, leaves and ears. The fitting was performed using the General Linear Models option of SAS.[11] As the amounts sprayed were not known exactly in all experiments, initial amounts were estimated from the regressions, regarding every plot which received a different spray as a separate class. Using this as a general, underlying structure, the contributions of stems, leaves and ears to the absorption of droplets were tested, as well as whether stems, leaves and ears showed different k values. The contribution of the area of the glass strips to droplet interception was examined in an exploratory model version which included the area of the glass strips. This contribution did not reach the 5% significance level and was neglected. The numbers of replicates of plant area measurements and deposition measurements differed between experiments. It was therefore tested how best to match the deposition measurements in the first and second experiments. This showed that the use of pseudoreplicates of plant areas, or the use of mean values for deposition, resulted in close to identical statistics. The use of pseudoreplicates was preferred, because this ensured that the variance and standard errors related directly to separate glass plates.

3 RESULTS

3.1 General investigations on crop architecture

The height of the leaves showed a linear relationship with the height of the flag leaf (Fig. 1A, regression in Table 2). The changes in leaf area were described in relation to the height of the flag leaf (Fig. 1B, regression in Table 3). This showed that the leaves near the soil reached their maximum size earlier in the season and

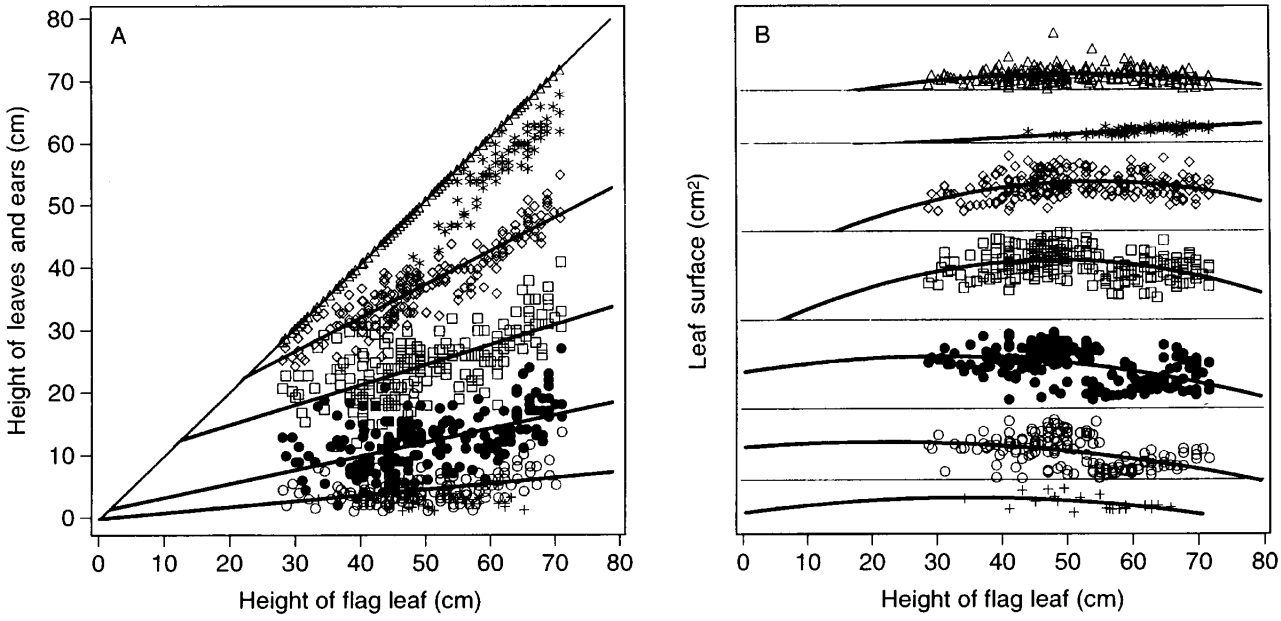

Fig. 1. Graphical representation of the crop architecture of spring barley. Stems sorted to height of flag leaf. Stems shorter than 50 cm belong in most cases to crop stage 48, all stems with ears were of stage 56. A. Leaf height and linear regression lines B. Total outer leaf surface in relation height of flag leaf. Lines represent second-order polynomial regressions. (△) Flag leaf, (*) ear, (◇) 1st, (□) 2nd, (●) 3rd (○) 4th, (+) 5th leaf below flag leaf.

TABLE 2
Regression Coefficients for the Relationship between Leaf Height and Stem Length

		Asympt. 95% conf. interval	
Leaf/ear	*Estimate*	*Lower*	*Upper*
Intercepts:			
Flag leaf (leaf 0)	0	−1·9	1·9
Ear	−7·5	−14·2	−0·8
Leaf 1	10·9	9·0	12·8
Leaf 2	8·7	6·9	10·6
Leaf 3	1·2	−0·6	3·1
Leaf 4	0·1	−2·3	2·5
Leaf 5	2·5	−5·1	10·1
Regression coefficients:			
Flag leaf (leaf 0)	1·00	0·96	1·04
Ear	1·02	0·91	1·13
Leaf 1	0·52	0·49	0·56
Leaf 2	0·31	0·28	0·35
Leaf 3	0·21	0·18	0·25
Leaf 4	0·86	0·04	0·13
Leaf 5	−0·003	−0·14	0·14

Positions of the leaves represent the interception point of leaf and stem. Ear height is measured at the ear base.

also withered earlier than the top leaves. An analysis of the relationship between stem area and stem length for both crop stages used in the present experiment is shown in Fig. 2. The stems in experiment 3 were relatively thin for their length. The decrease in regression coefficient may indicate more than isomorphic stretching of the stems with growth, but may also be related to the slightly higher crop density in the third than in the second experiment. The distribution of stems at the different crop stages is shown in Fig. 3. The results show a skewed distribution with more short than tall stems.

3.2 Plant surface measurements in relation to deposition

To analyse growth-stage effects on crop surface parameters, the profiles of the numbers and areas of stems, leaves and ears per crop stratum were compared between the two growth stages. Figure 4 gives the crop architecture per 10-cm layer. Selected summary and statistical parameters in relation to crop architecture are given in Table 4. Figures 4A and 4B show the total areas of stems and leaves for both crop stages. The total area per layer was calculated as the sum of the products of the number of stems, leaves and ears with the corresponding mean surface areas. Figures 4C and 4D show that ageing of the crop also changes the vertical distribution of leaf sizes. The largest mean leaf areas were measured at approximately 20-cm height at crop stage 47 and at 35-cm height at crop stage 56. A relatively small leaf area of the lower leaves in the high crop coincided with observations that this layer contained many yellow and brownish, shrivelled leaves. Finally, Figs 4E and 4F show that there is a general reduction in the number of leaves per layer with crop stage. As new leaves are typically formed at the plant apex, a

TABLE 3
Linear Regression Coefficients for the Relationship between Leaf Area and Flag Leaf Height

Leaf/ear	*Intercept*	*Linear coefficient*	*Quadratic coefficient*
Flag leaf (leaf 0)	−11·62	0·80	−0·0784
Ear	−4·21	0·17	0·00025
Leaf 1[a]	−23	1·89	−0·0174
Leaf 2	−9·4	1·78	−0·0185
Leaf 3	21	0·57	−0·00934
Leaf 4	9·3	0·27	−0·00635
Leaf 5	0·7	0·49	−0·00724

[a] Leaf numbers indicate position relative to flag leaf.

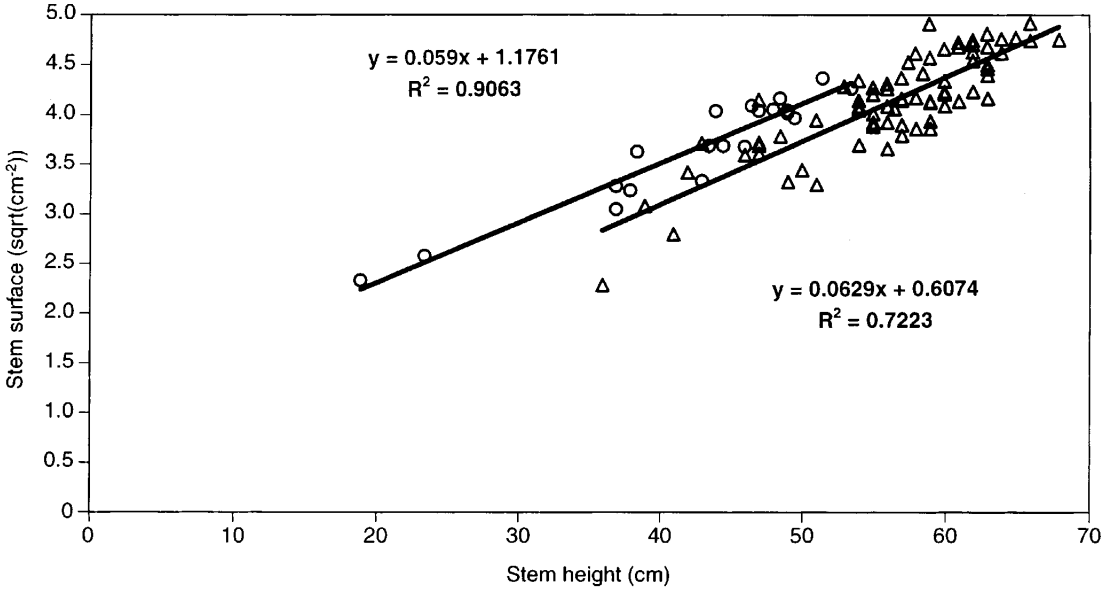

Fig. 2. Relationships between stem area and stem lengths in spring barley at (○) crop stage 48 and (△) crop stage 56. Stems at crop stage 56 are relatively thin.

reduction in leaf density per layer must reflect a stretching of the crop.

3.3 The deposition model

Under the assumption that drift of droplets out of the crop canopy is negligible, the deposition of the non-volatile fluorescent dye on the glass strips can be considered to represent the amount of fluorescent dye which was still in the air at the height of measurement. The measurements show that this amount decreases with penetration of the spray into the crop (Fig. 5). The steeper curves in the dense crops demonstrate more interception of droplets with height than in the thin crops. To give an impression of the variation which seems inherent to in-situ deposition measurements, Fig. 5 shows all separate measurements at every height.

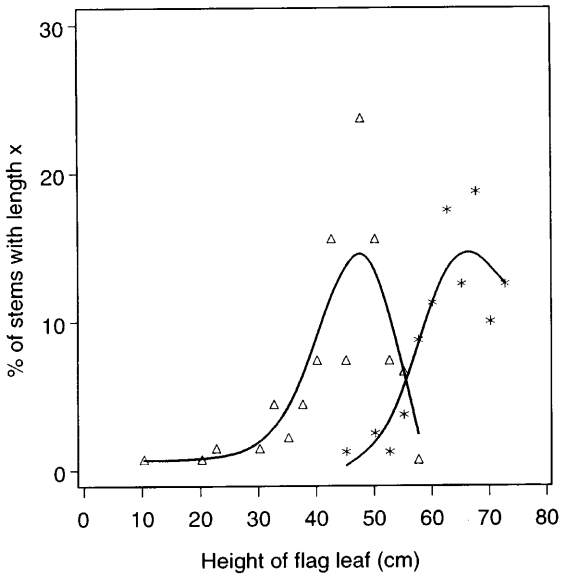

Fig. 3. Frequency distribution of stem lengths in spring barley at stages 48 and 56 for 2·5 cm intervals. (△) Crop stage 48, $n = 135$, mean = 43·2, std = 7·4, skewness = −1·5, curtosis = 3·97, cv = 17·3. (*) Crop stage 56, $n = 80$, mean = 62·6, std = 5·9, skewness = −0·67, curtosis = 0·41, cv = 9·5.

Table 5 gives the outcome of the regression analysis. In the first model (M1) all areas were assumed to have the same interception coefficient. In the second model (M2) separate interception coefficients were allowed for stems, leaves and ears. The residuals resulting from both models showed that the model assumptions agreed well with the data for all heights except at ground level. Here, relatively many positive residuals pointed to an underestimation of the observed deposition by the model. From these results the following conclusions can be drawn. (1) The contributions of the areas of stems, leaves and ears to the detailed regression model (M2) were all significant at the 5% level (as indicated by the 95% confidence limits in Table 5). This implies that, whenever a crop had stems, leaves or ears, the area clearly affected the interception of droplets. (2) The comparison of models M1 and M2 represents a test of the hypothesis that the different plant areas show different interception coefficients. The variance ratio when comparing the fits of models M1 and M2 was 1·7 which is less than the F^2_{132} value of 3·07. This lack of significance between the two models despite a reasonable number of observations must result from the high variation in the data which showed a coefficient of variance of 35%. Since the F-test shows no significant increase in fit going from model M1 to M2, this justifies using a simple model with an averaged k value. As the concentration of pesticide on the plant areas is given by $C(x)$ times k this also implies identical concentrations on all plant parts. A disadvantage of such a simple approach is that the relative contributions of the different crop

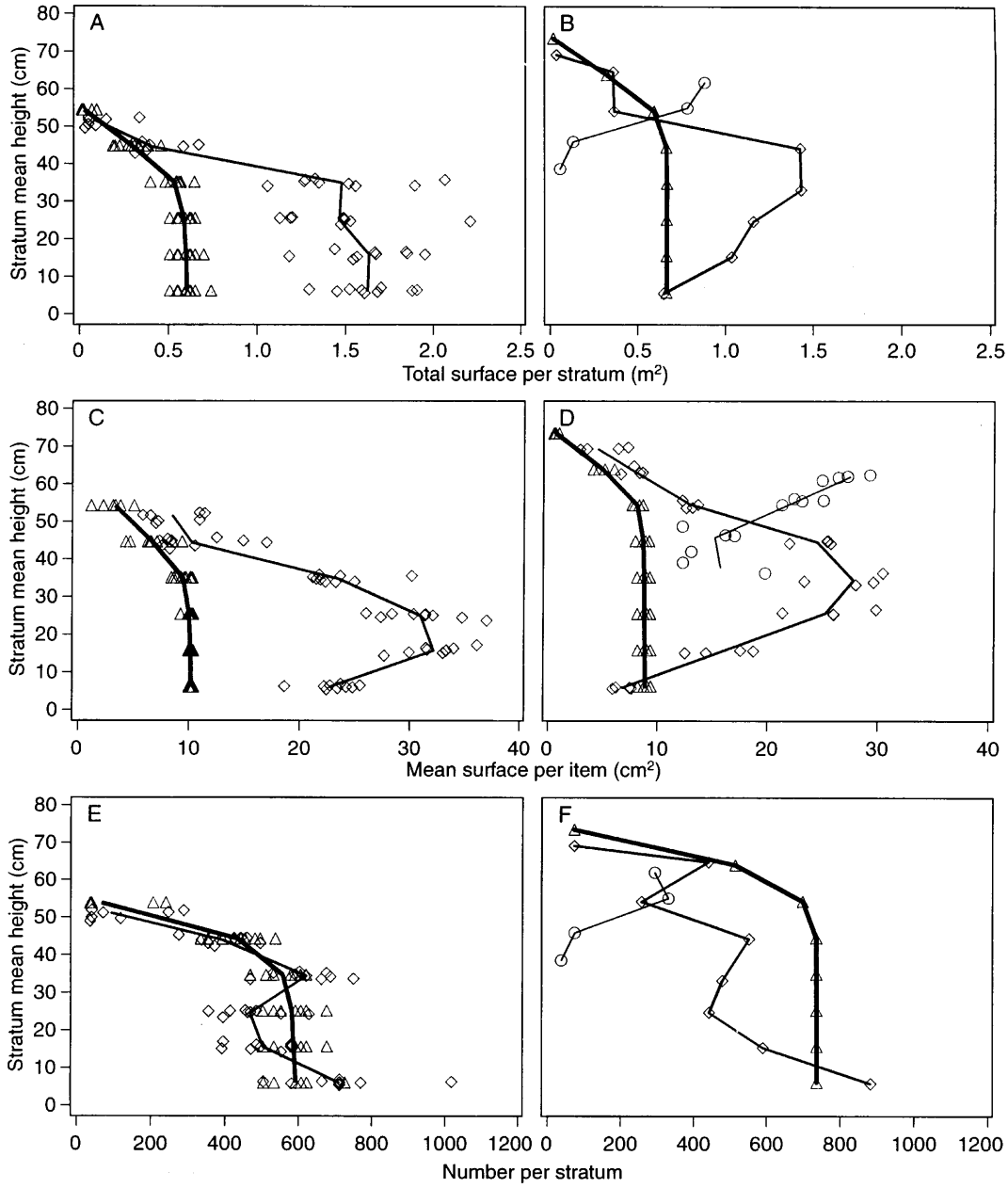

Fig. 4. Stratified crop architecture of a spring barley crop at stages 48 (left) and 56 (right). A and B show the total surface of each plant given as the product of area and number of each item. C and D show the mean surface area per item for stem, leaf and ear, measured as the vertical projections. E and F show the frequencies m^{-2} of stems, leaves and ears per 10-cm layer of the crop. Lines connect the averages of all nine plots at stage 48 or four plots at stage 56. (△) Per plot values for stems (◇) per plot means for leaves. (———) = Stem means. (———) = Leaf means. (———) = Ear means.

surfaces are averaged. This limits interpretation and understanding of the processes and makes the k value case-specific. For this reason the complex model was preferred and used henceforth to analyse deposition.

The results are shown in Fig. 6. In all calculations 100% was used as the initial amount sprayed. In this way one can read directly from the graph what percentage of a particular application rate would be intercepted by the crop or deposited on the soil, thereby facilitating comparison with other studies. Calculations were based on the observed mean area of the nine plots of experiment 2, and of the unchanged crop of experiment 3 as the input for the crop area distribution. Reduced density values were calculated from this by taking 75, 50 and 25% of each variable. This implies that possible phenotypic changes due to lower tiller density, such as differences in leaf width, are not included. The principles being the same for both crops, we decided to focus on the high crop which showed the largest number of different area types. Figure 6A presents the canopy surfaces summarised per stratum for all crop parts. The ears fill in a marked percentage of the area of the top layers. Figure 6B shows the calculated amount of pesticide remaining in the air at the different heights. Most

TABLE 4
Selected Summary and Statistical Parameters in Relation to Crop Architecture: means and standard deviations of two plots representative of the present spring barley crop

	Stems			*Leaves*			*Ears*		
Plant Height	*Number* (m^{-2})	*Mean area* ($m^2\ m^{-2}$)	*Std*	*Number* (m^{-2})	*Mean area* ($m^2\ m^{-2}$)	*Std*	*Number* (m^{-2})	*Mean area* ($m^2\ m^{-2}$)	*Std*
Sub-plot 3 in plot 1 of the spring barley crop at stage 48 (frequency factor 41)									
60	41[a]	1·04	0[c]	41	11	0			
50	451	2·04	0·76	451	15	9·4			
40	615[b]	2·82	0·84	697	22	11·8			
30	615	3·22	0·15	492	31	8·5			
20	615	3·22	0·15	492	34	7·7			
10	615	3·22	0·15	779	24	7·8			
Plot 4 of the spring barley crop at stage 56 (frequency factor 37)									
80	74	0·16	0·16	74	2·9	1·52			
70	518	1·92	0·97	444	7·8	3·32	296	9·3	0
60	703	2·63	0·69	259	13·7	6·64	330	7·4	0·05
50	740	2·82	0·49	555	25·6	8·96	74	5·2	2·10
40	740	2·83	0·45	481	29·8	6·78	37	3·9	0·65
30	740	2·84	0·45	444	26·0	2·80	0		
20	740	2·84	0·45	592	17·4	7·18	0		
10	740	2·84	0·45	888	7·3	4·76	0		

[a] This represents one measured stem multiplied by the frequency factor as mentioned in Table 2.
[b] If differences occur between mean areas at equal stem densities this indicates that many stems did not reach the upper limit of the 10 cm stratum.
[c] Standard deviations relate to the actually observed numbers and are 0 for a single stem.

of the pesticide is captured by the plants during the first 40 cm of its journey through the crop. Comparing the results of the high and low crop shows that the efficiencies of the upper 40 cm of both crops were apparently nearly equal. Figure 6B furthermore shows that about 20% of the sprayed amount reaches the soil in the high spring barley crop, and about 30% in the low crop. In the 25% stem density situations these values have increased to about 65 and 72, respectively. This shows that thinning the crop strongly increases the amount of pesticide reaching the soil. Figure 6C shows how much of the sprayed pesticide is captured at the different strata by the stems, leaves and ears. The ears make a strong contribution to spray capture, which is caused by their large effective area and the high amounts of pesticide still in the air at the higher strata. Figure 6D presents the concentrations of pesticides on the respective crop parts which can be calculated as the

TABLE 5
Analyses of the Amount of Pesticide Deposited on Glass Plates at Different Heights in the Crop[a]

	k *stem*	k *leaf*	k *ear*	k *all*	*c1*	*c21*	*c22*	*c23*	*c3*	*DF total*	*DF resid.*	*SSR*	*MSR*	*VR of M1 over M2*
Model M1, one single interception value														
Estimate				0·13	4·92	3·82	4·22	4·21	5·07	138	132	12·08	0·092	1·7
Lower CL				0·11	4·79	3·63	4·05	4·04	4·93					
Upper CL				0·15	5·05	4·00	4·40	4·39	5·20					
Model M2, different interception values for area of stems, leaves and ears														
Estimates	0·20	0·09	0·21		5·02	3·75	4·18	4·16	5·19	138	130	11·76	0·090	
Lower CL	0·10	0·03	0·03		4·81	3·55	4·00	3·97	4·97					
Upper CL	0·30	0·14	0·39		5·23	3·95	4·37	4·35	5·41					

[a] Results of regression calculations according to eqn (4).

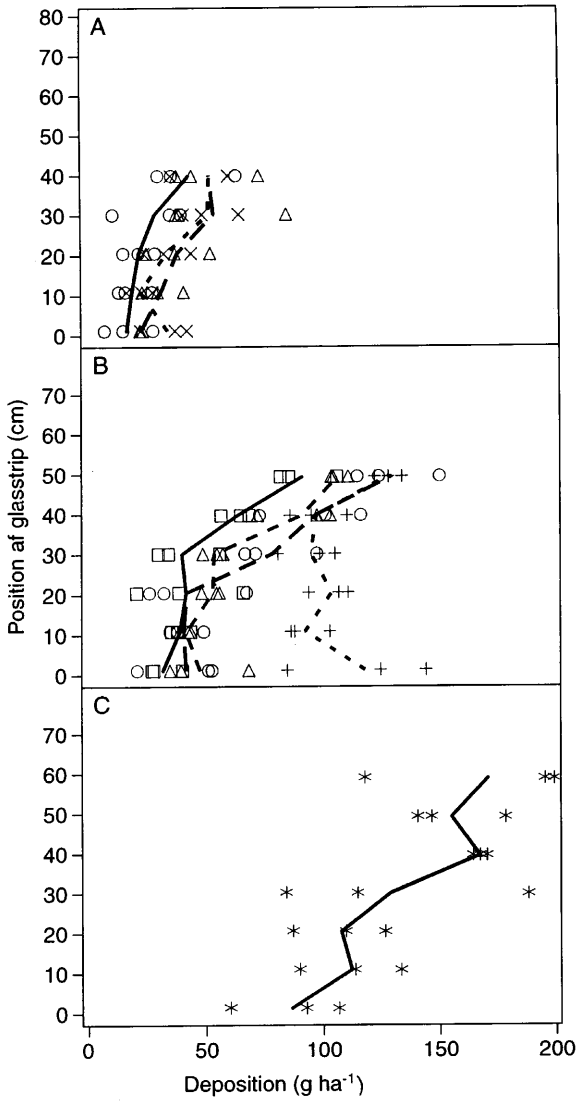

Fig. 5. Measured deposition on glass strips in spring barley. (A) stems with leaves, (B) stems with leaves and ears, (C) stems. Lines connect plot means. Finer dashing of the lines indicates thinner crop canopy. A = crop stage 48. Plots (○) 2, (△) 3 and (+) 4, in order of reducing crop surface, (see Table 2.1). B = crop stage 56. In order of reducing crop surface, squares, rounds, triangles and crosses represent measurements on subplots 5·1, 5·2, 5·3 and 5·4. C = 'stems' only experiment, stars = individual measurements.

product of $C(x)$ and k. This shows that the leaves actually catch fewer droplets per total area than the stems and ears. If the concentration on the leaves is expressed relative to the upper side only, the values double and become almost identical to the stem and ear concentrations (Fig. 6D, broken line). Note that the concentration on the soil must not be inferred from Fig. 6D but from Fig. 6B.

4 DISCUSSION

The area of all investigated plant parts, when present, contributed significantly to the interception of droplets by the crop. All these plants parts should, therefore, be included in models for pesticide deposition. Yet, given a coefficient variation of 35%, no significant differences were found for the k values of stems, leaves and ears. Accordingly, a model with a single k value could, in principle, give an accurate enough description of the spray interception. As explained above, the model with different k values was nevertheless preferred in the present study.

Using the latter model the interception efficiencies per total outer area showed different values. The stems and ears, which represent vertically standing, cylindrical plant parts were found to have k values of approximately 0·2. The k value of the leaves was 0·09, which was slightly less than half of that of the stems and ears. This may be due to the fact that, compared to stems and ears, which trap droplets on all sides, the leaves normally trap droplets mainly at their upper surface. However, for this explanation the barley leaves should not be placed at very high angles or vertical, since this would result in high deposition again. The latter was shown by Wirth *et al.*[5] in an experiment where the (two-sided) droplet retention of whole barley leaves in a vertical position was as much as 80% of the horizontal value, when sprayed with a flat fan nozzle.

The present model was based on a limited data set and excludes several aspects of the field situation. Firstly, the model deals selectively with concentrations, excluding any detailed description of changes in droplet spectrum during spray penetration and changes in flight angles of the droplets on their way through the crop. Possible effects of the low windspeed (see Section 2.1) on the deposition in the crop were regarded as negligible, and not included in the model. Accordingly, the model includes no parameters to describe effects of wind speed on the deposition pattern. Secondly, the model uses measurements of pesticide deposition and plant surface to predict amounts in the air and on leaf surfaces. Measurements were restricted to amounts in the air. A check of the predicted plant surface deposits to verify the accuracy of the inverse relationship assumed by the model between plant area and amount of pesticide in the air would have required measurements of plant parts such as stems, leaves, and ears. Due to the emphasis in the present approach on measuring the amount of non-intercepted droplets on glass strips, deposition on plants was not measured, since it was considered that this necessarily had to be complementary. As an easy way of validating the model predictions, however, this should be included in future experiments.

The assumption that a given amount of leaf area per stratum takes away a constant percentage of the droplets allowed an accurate description of the disappearance of pesticide droplets from the air. A practical advantage of the approach used is that it was based on only two kinds of data: plant surface and pesticide

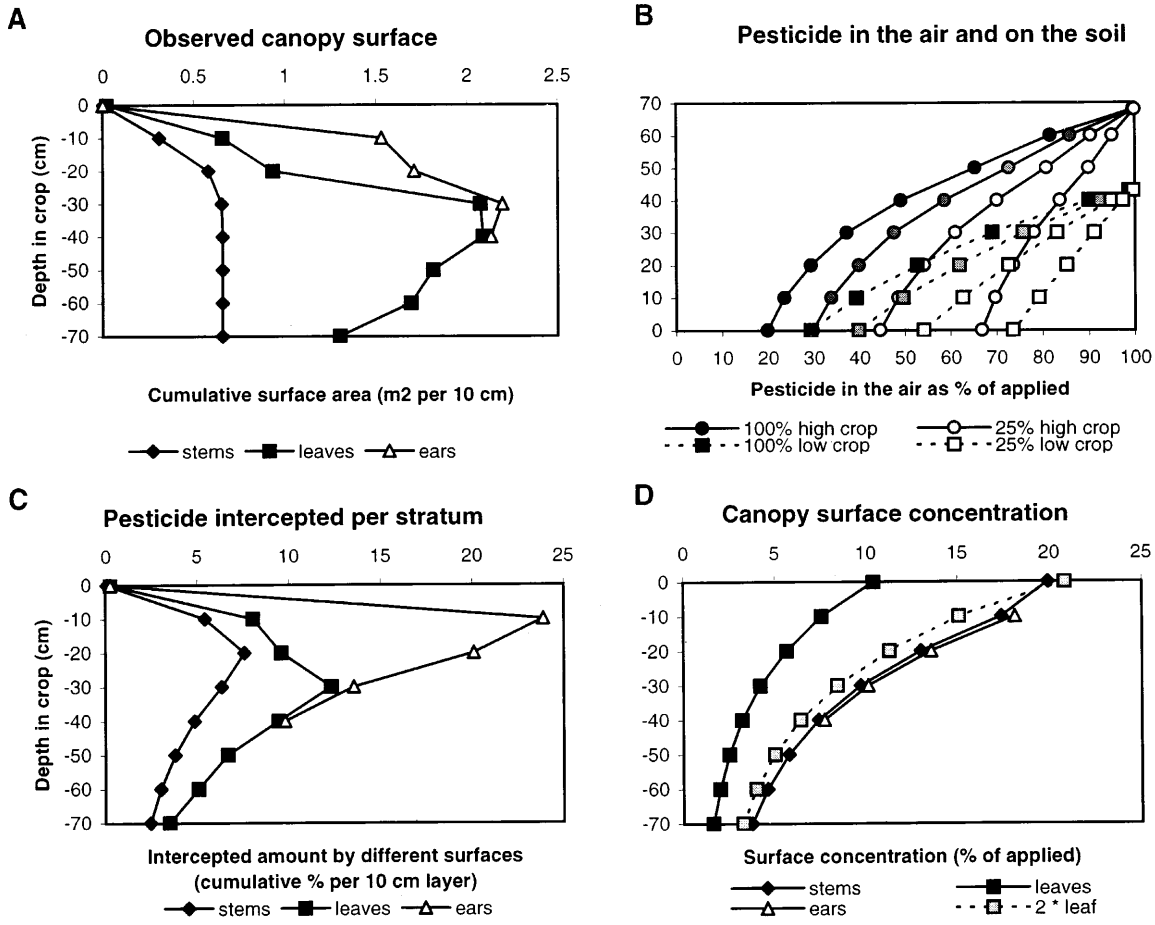

Fig. 6. Results of the deposition model. A. Observed total plant surface as composed of stem surface, leaf surface and ear surface. B. Calculated amounts of pesticide still in the air at the indicated heights above the soil (squares = crop stage 48, mean of 608 tillers m^{-2}, dots = crop stage 56, mean of 756 tiller m^{-2}). C. Calculated amount of pesticide absorbed by the stems, leaves and ears. D. Calculated plant surface concentrations for stems, leaves and ears.

deposit on glass strips, which are easily obtained from the field. The measuring of plant surface is a standard technique. The use of large glass strips to measure deposition avoids the elaborate measuring the deposits from real plant surfaces. Attempts to compare the present results with literature data were somewhat hampered by the fact that most observations have been conducted in winter wheat. In this crop Cilgi and Jepson[4] measured concentrations on flag leaves of approximately 15 to 18% (one-sided), on first leaves of approximately 10 to 13%, and depositions on the soil of 6 to 16%, at different crop stages between 47 and 82. As the flag leaves were placed between 50 and 70 cm in the present crop at stage 56 (Fig. 1) we can read the leaf area concentrations from Fig. 6C in the heights between − 10 and − 20. This yields comparable values of 12 to 17%. The above also shows that residues on the soil are slightly higher (about 20% at crop stage 56) in the present experiment than in the winter wheat crop of Cilgi and Jepson.[4] Comparable values for winter wheat may also be found in other studies.[1,2,7]

The relationships between plant area and deposition such as given by eqn (4) can be applied to connect three measurements that are generally used for pesticide deposition: the deposition per tiller (ml per tiller or % per tiller), the deposition per cm^2 (ml cm^{-2} or % cm^{-2}) and the percentage of the sprayed amount that reaches the soil (% m^{-2}). In theory, results from experiments with different plant densities, crop stages and application rates can be compared by means of these relationships. For this purpose they would have to be normalised to a standard situation, for instance an application rate of 200 litre ha^{-1}, a crop density of 600 tillers m^{-2}, and a standard crop area profile reflecting a particular growth stage. In practice, studies on pesticide deposition hardly ever contain sufficient information about plant area to perform such normalisations. To allow for such inter-experimental calibrations, and in order to let pesticide deposition experiments play a role in the calibration or check of models for pesticide deposition, it seems advisable, therefore, to include stratified measurements of stem, leaf and ear surfaces, or a description of crop architecture as standard aspects of future deposition studies.

Finally, the description of the crop architecture in the Figs 1, 2 and 3 indicates that the growth of spring

barley follows a strict pattern. The present data set does not allow a full exploration of the rigidity of this growth pattern nor its relationships with the actual plant growth in relation to variety and environmental factors such as temperature, crop density, soil moisture and fertilisation, because we have data only from a single field and two crop stages. Nevertheless, the results look very promising in the sense that with some more research on this point, it may be possible to link the present crop description to crop growth simulations such as, for example, have been worked out by Graf[10] or Christensen *et al.*[12] As long as a crop shows growth, which actually is the period during which pesticides are normally applied, one could then model the development of the full plant architecture in the field, and simulate deposition from this. This could be used to create deposition tables for different crop conditions which would assist farmers in predicting deposition on plants and soil in a particular crop. To do this, one would need two things: a reference growth pattern of the particular seed variety determined under controlled conditions, and information on how this standard pattern depends on field conditions such as sowing date and density, fertilizer and climate.

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